# Motion Studies of Cathode Roots in High Current Arcs using an Optical Fibre Array based Imaging System

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**Abstract** This paper presents an integrated portable measurement system for the study of high speed and high temperature unsteady plasma flows such as those found in the vicinity of high current switching arcs. The system permits direct and non-intrusive measurement of arc light emission images with a capture rate of 1 million images per second (1MHz), and 8 bit intensity resolution. Novel software techniques are reported to measure arc trajectories. Results are presented on single high current (2kA) discharge events where the electrode and arc runner surfaces are investigated using 3D laser scanning methods; such that the position of the arc roots on the runner can be correlated to the measured trajectories. The results show evidence of the cathode arc root stepping along the arc runners, and regions of where the arc runner is eroded by a stationary arc.

**Keyword.** electric arc, arc imaging, current limiting circuit breakers.

## 1. Introduction

There are many engineering applications in aerospace, combustion and electrical systems where the medium of interest is a gas at high temperature in an unsteady flow regime. Improved understanding of critical flow parameters is required to enable the optimisation of these devices and systems. Using high speed imaging and image-processing techniques, spatially and temporally resolved parameters including object location, size, area, number, velocity and direction of movement can be determined from the recorded images.

This work builds upon an established methodology described fully in [1,2], and with an established research programme associated with current limiting devices, for example [3-6]. In this work an integrated system for the measurement of transient displacement and velocity in complex high speed and high temperature unsteady gas flow is described. The optical fibre array imaging system is defined as an Arc Imaging System (AIS). The system presented here has been developed commercially, [7] and is based on the system described in [1, 2]. Table 1 provides an overview of the old [1, 2] and new [7] systems. The key advantages of the new AIS over the old system, is that the temporal sample rate is increased by a factor of 2, the light level resolution of the system is increased by a factor of 4, and the gain flexibility allows a significant improvement in the control of the system sensitivity. An initial investigation of the system was used to investigate the motion of the arc roots. It was shown that under some conditions that the arc roots can move backwards as the arc enters the splitter plates, [8].

## 2. Methods

The test system has been fully described in previous research publication, [1,2]. In brief a capacitive discharge system is connected to a flexible test apparatus, allowing a peak short circuit current of approximately 2 kA over a 10 ms half cycle. The configuration of the arc chamber is shown in Fig1, where the fibre positions are shown.

For the tests conducted here, the vent was 15% open, and the moving contact was connected to a high speed solenoid opening device, (>6 m/sec), [5].

| System | Old AIS | NewAIS |
|---|---|---|
| Maximum Framing or sample rate | 500kHz | 1MHz |
| Maximum Number of Optical Fibres | 90 | 1024 |
| Light Intensity Resolution | 6bit (0-63) | 8bit 0-255) |
| Memory Allocation | 4K | 512K |
| Data storage time at Maximum Framing rate | 8ms | 500ms |
| Sensitivity | No Control | x1 - x32 |

*Table 1. System Specification*

## 3. Results

The main focus is on the correlation of data between the imaging system [7] and a surface scanning system using a TaiCaan Technologies XYRIS 4000CL [9]. Fig 2, shows the arc voltage and current from the experiment. The time base shows the contacts opening after the pre-set time of 2ms. The arc moves rapidly to the arc chamber in approximately 1.2 ms, and then shows a number of pressure wave effects as the arc attempts to fully enter the arc splitter plates. The current peaks at 1.7 kA after 1.2ms. Fig 3 shows the light intensity output from selected fibres along the cathode root, while Fig 4 shows the fibre positions superimposed on an image of the arc chamber. The time base in Fig 3 has been reduced by 2000µsec. Thus the peak intensity for fibre positions U and L corresponds to the time position ~3000µsec, (first peak is at 2963µsec). The second peak in fibre U, suggest the arc is moving backwards, and is only evident in fibre position, U; [8].

Fig 5 shows an arc image at 2947µsec. The arc image is created without using a group contouring algorithm used previously in [1, 2], as in this study were are concerned with detailed events during the arcing process that could be lost with group contouring, such as multiple arc paths.

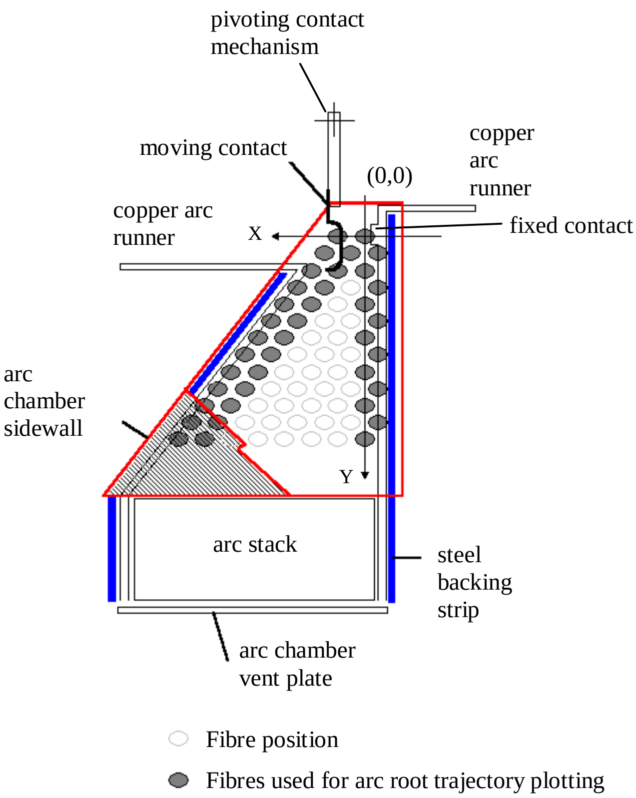


*Fig 1. Flexible test apparatus with fibre positions*

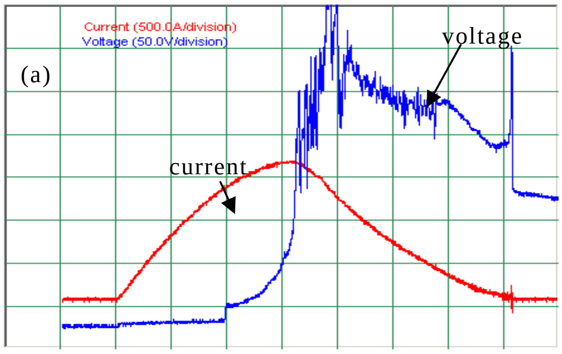


*Fig 2. Arc Voltage and Current, Time base 1ms/division*

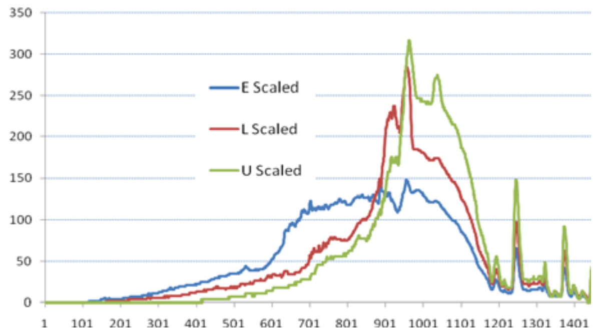


*Fig.3 Scaled Intensities vs Time (-2000µs)*

*Fig. 4 Fibre positions along the cathode runner, from left to right BH,AS,AF(highlighted),U,L and E*

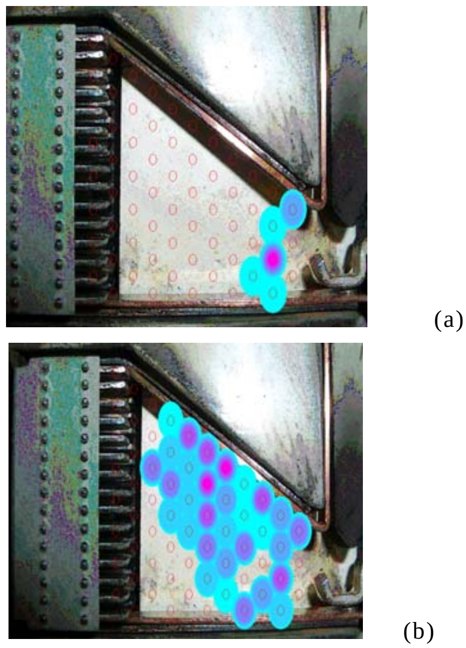


*Fig. 5 Arc images using filters based on maximum value at fibre U At a)2947µs, and b)2959µs*

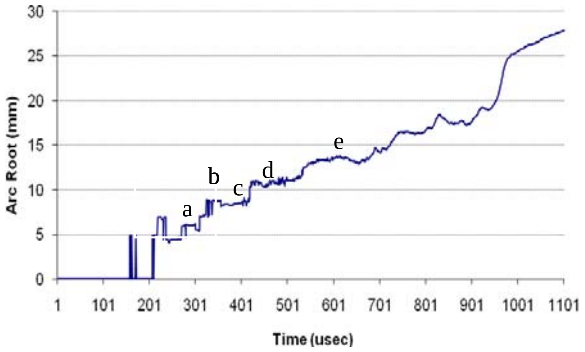


*Fig. 6 Close up of cathode root motion between 2000-3000μsec, (U1 peak at 964 and U2 peak at 1036*

## 4. Arc Plotting

There are two modes of arc plotting, using dynamic thresholds, or using fixed thresholds, [1,2]. In both cases contours are plotted as a fixed percentage of a maximum light intensity value. With dynamic thresholds the maximum value is the maximum light intensity across all the fibres for a given frame number. With fixed thresholds the maximum value is the maximum light intensity across all the fibres for all frames. Thus for the former the contours are drawn at different light levels for each frame, and this method is best suited for viewing the arc when the light intensities are low, for example at the start of the arc. The latter is best suited for an overview of the arc process when the arc is in the chamber, the contours will be fixed, allowing a systematic comparison of arcing events. The current study relates to arcing events in the chamber, the contour levels are thus fixed. For the experiment the maximum light level was 850, while the events around fibre U have a maximum of 350, see Fig.3. The maximum light level thus corresponds to 41% of the full data set value. Thus the contours are closely bunched around the 42%-30% light values, and fixed for all images, [8].

Fig 5a shows the arc column at 2947 μsec having transferred from the moving contact to the anode arc runner, and conducting to the cathode runner region, outside the fixed contact region. Fig 5b shows the arc 12 μsec later, at 2959 μsec, with the arc column now in the middle of the chamber. This image shows the arc column with a single root on the cathode, but with two conducting paths to the anode surface. This event occurs for the duration of ~10μsec before the arc forms a single column to the anode.

## 5. Arc Root Plotting

The arc root plotting method was first reported in [10], and is further discussed in [1, 2]. The method is based on an intensity based position averaging technique over selected fibre positions near the surface of the runners (shaded fibres in Fig 1). For the cathode root, the first fibre position B is allocated Y =1mm, and the AZ fibre Y= 40mm (see Fig's 1 and 4). In this study the method has been developed to allow for accurate positioning. The averaging method now allows for 10 nm resolution in the positioning along the Y axis. Thus with fibres positioned 3mm apart we are able to determine the position of the centre of the arc root to 10nm. The results for the cathode root motion are shown in Fig. 6. It shows the cathode root moving at 2200μsec to the 5-7mm position. The cathode root then appears to be stationary in regions a,b,c,d, and e; with the corresponding positions, a=6mm, b=8.5mm, c=8mm, d=11mm, and e=13mm.

## 6. Surface Analysis Methods

To provide insight into arc root motion, both anode and cathode runners were removed after a single test and analysed using a 3D con-focal laser profiler, [9]. The anode runner surface exhibits minimal surface damage, however the cathode surface exhibits significant damage, as shown in Fig.7. The image shows the Ag/C contact surface on the left where there is substantial darkening of the Cu surface. In sections B,C and D, the root appears to have a preference for the upper edge of the runner, which is consistent with the thermal properties of the arc. The positions of the eroded surface edges (b,c) and (e) correspond to the regions identified in Fig.6.

In region C, of Fig.7 there appears to be a large number of smaller cathode spot regions in the middle of the runner. These spots become more pronounced further along the runner to the right, as there is less darkening of the cathode surface. Further inspection of surface area D is shown in Fig 8 and 9, with a CCD microscope camera view of the spot feature F, in Fig 8. The microscope image clearly shows the darkened area around the cathode spot. The green line and data value correspond to the vertical height in microns of the laser spot also shown as a cross-hair in the centre of the image. In Fig.8; 4 cathode spots become apparent. These are labelled F,G,H,I; in the 3D surface data. The first three regions are apparent in the photographic image in Fig 7, but not the small feature I. Fig 9, further enhances the image of the cathode spots with a 2D section of region F, exhibiting a crater effect at the leading edge, while the trailing edge shows a build up of material.

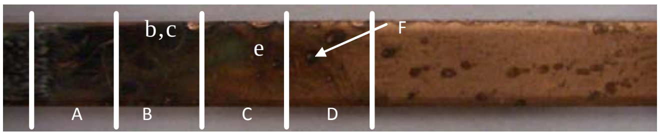


*Fig 7. Image of the cathode surface after experiment, with approximate positions of 3D surfaces. Vertical lines have 5mm spacing*

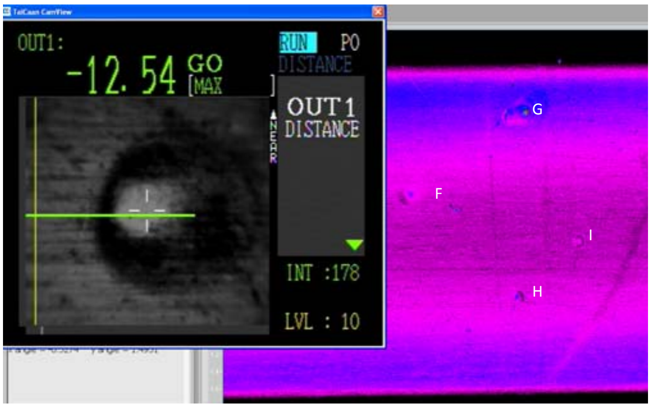


*Fig. 8, Detailed view of region D, with an inset CCD camera image of spot F, (CCD visual area 1mmx1mm).*

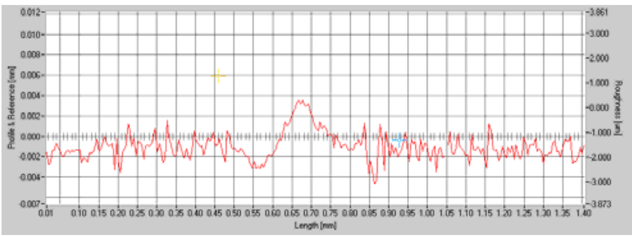

*Fig.9, 2D cross section of region F.*

## 7. Discussion and Conclusions

There are three observations to be made from the results presented. Firstly it has been shown that the cathode arc root steps along the arc runner. This is not evident in the arc root motion along the anode surface [8]. This is shown in both the arc root plotting method in Fig 6, and in the erosion patterns on the cathode surface in Fig 7. The positions where the arc has remained stable are correlated between the two data sources, this is further evidence of cathodic arc root stepping, [11]. Secondly; the cathode arc root has been shown to move backwards, in Fig.3. This is expected to be related to the period when the arc in stationary. Thirdly the results show a number of smaller regions of damage along the arc runner. Investigation of these regions, using an optical surface profiler; have shown that they correspond to small regions which have been rapidly heated and then cooled. The cathode surface has been smoothed and distorted as shown in Fig's 8 and 9.

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